

# PlumeSat: A Micro-Satellite Based Plume Imagery Collection Experiment

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## PlumeSat: A Micro-satellite Based Plume Imagery Collection Experiment

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### Abstract

This paper describes a technical approach to cost-effectively collect plume imagery of boosting targets using a novel Micro-satellite based platform operating in low earth orbit (LEO). The plume collection Micro-satellite or PlumeSat for short, will be capable of carrying an array of multi-spectral (UV through LWIR) passive and active (Imaging LADAR) sensors and maneuvering with a lateral divert propulsion system to different observation altitudes (100 to 300 km) and different closing geometries to achieve a range of aspect angles (15 to 60 degrees) in order to simulate a variety of boost phase intercept missions. The PlumeSat will be a cost effective platform to collect boost phase plume imagery from within 1 to 10 km ranges, resulting in 0.1 to 1 meter resolution imagery of a variety of potential target missiles with a goal of demonstrating reliable plume-to-hardbody handover algorithms for future boost phase intercept missions. Once deployed on orbit, the PlumeSat would perform a series phenomenology collection experiments until it expends its on-board propellants. The baseline PlumeSat concept is sized to provide from 5 to 7 separate flyby data collects of boosting targets. The total number of data collects will depend on the orbital basing altitude and the accuracy in delivering the boosting target vehicle to the nominal PlumeSat fly-by volume.

### 1.0 Introduction

We at Lawrence Livermore National Laboratory (LLNL) propose that the Missile Defense Agency (MDA) initiates another fast-paced Clementine-like mission to develop the PlumeSat as a versatile platform for multiple near-term plume imagery data collection and space-based intercept experiments. For Boost Phase Missile Defense the plume-to-hardbody handover and the final aim-point selection is an area that is severely lacking experimental data points to validate system performance. Other than one Delta-Star (or -180??) experiment, against a small upper stage, there is little data on the variety of potential target types (both solid and liquid boosters) and possible viewing geometries (day and night-time observations both with and without earth background, etc). A significant quantity of plume imagery has previously been collected during a variety of phenomenology experiments over the last two decades. However all of these data collects have been made from large standoff distances using high altitude airplanes, ground telescopes, or from space platforms, which have resulted in low resolution imagery, at less optimum aspect angles, and with closing geometries not found in intercept engagements. We propose to use an orbiting sensor platform, with the ability to maneuver to within a few kilometers of a boosting target, and to perform a series of high-speed fly-bys with a robust sensor suite of both passive and active sensors including both LWIR and an Imaging LADAR sensor. We propose to provide sufficient on-board  $\Delta v$  to enable multiple (5-7) data collects of different boosters using this same set of imaging sensors. We will have for the first time an optimum system to collect both plume and hardbody imagery at both high resolution and at the correct engagement geometries, needed for boost phase intercepts. This will provide the type of input for real-time GN&C, plume-to-hardbody handover and aimpoint selection algorithms to be run both on-board the sensor platform and on the ground to further perfect their development for operational BPI platforms. These algorithms can be uploaded throughout the mission and tested during successive fly-bys. Finally at the conclusion of the data collection portion of the mission, we can use the PlumeSat platform to attempt a boost phase intercept from orbit. An additional benefit of this development effort is to enable the flight qualification of a Liquid DACS pumped propulsion system under development for MDA and

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designed for use in the Advanced Technology Kill Vehicle (ATKV) a concept vehicle conceived by LLNL. Furthermore this test program will push the technology envelope of micro-satellite systems and support the development of future space control platforms for the Department of Defense.

The critical enabling technology for this important capability is the development of an agile micro-satellite or MicroSat. A MicroSat is a small satellite weighing only a few tens of kilograms but carrying onboard a host of lightweight sensors, inertial navigation instruments, state-of-the-art avionics and a GPS receiver. When equipped with a propulsion system and guidance, navigation and control software, the MicroSat has the ability to maneuver precisely in space in both orientation and translation. When further equipped with smart vision based image analysis software, the MicroSat can autonomously perform functions such as rendezvous with another object, close-in inspection, and even execute a dock with another satellite, a capability that has already been demonstrated by LLNL in our high fidelity ground test apparatus. Ground command and control support can be minimized and used only to augment and enhance the vehicle's performance by providing ground truth knowledge, such as ephemeris data. MicroSats of this type can also function in a tele-robotic mode, with a man-in-the-loop, to more effectively execute complex (less predictable) maneuvers and to provide a manned presence on-orbit (if only in surrogate form) when and where one is required.

This technology has been in development at LLNL since the late 80's starting with the Brilliant Pebbles and the Clementine programs. For the past several years it has continued as part of the Clementine 2 project and the subsequent MicroSat Technologies Program, and currently as part of the Non-toxic Pumped Propulsion Development Program for MDA. Several prototype ground test vehicles have been built with fully functioning propulsion systems, avionics, and guidance and control software [1]. Significant progress has been made in the development of lightweight, non-toxic, pumped propulsion, the integration of advanced COTS sensors and compact avionics along with the development of precision guidance and control and dynamic ground flight-testing. A summary description of some of our MicroSat developments was presented at a recent IEEE Aerospace conference [1]. The capability for the autonomous execution of vehicle maneuvers and the precision docking with another object, have been demonstrated over the past several years at LLNL's dynamic air-bearing ground flight facility.

With a fast paced effort, we estimate that a PlumeSat can be developed within two years<sup>1</sup> and flown past several targets during the third year. The approximate cost to develop the PlumeSat itself will be in the range of \$75 M to \$100 M depending on the amount of development selected. Adding launch and operational costs will bring the estimated program budget to \$85M to \$125M, depending on the choice of the launch vehicle and not including the cost of the target vehicles. The following sections provide additional supporting technical detail for mission analysis, PlumeSat spacecraft design, relevant MicroSat technology, launch vehicle options, and a preliminary schedule and cost analysis.

## 2.0 Proposed Operational Concept

The basic operational concept of a PlumeSat is to collect boost phase plume imagery as shown in Figure 2.1 and can be further described as follows. One or more PlumeSats may be deployed in a high-inclination (e.g. polar) near-circular low earth orbit at a nominal altitude of 400 km. In preparation for a plume collection experiment, a PlumeSat will transfer into an elliptical orbit with its perigee at a desired altitude (100 km to 300 km) and location depending on the burnout altitude and location of the boosting target. The PlumeSat can accomplish this by firing one of its thrusters to reduce its forward orbital velocity. The exact amount of  $\Delta v$  reduction is dependent on the desired altitude at perigee. The PlumeSat can also make small orbital corrections in both inclination angle and azimuthal angle in order to achieve a more optimum target closing-angle, at the cost of additional  $\Delta v$ . By properly timing a cooperative launch of a target missile, the PlumeSat will arrive at the correct location to observe both the launch and the boost phase of the target launch vehicle. The PlumeSat will be able to observe the high altitude plume imagery at close range including the endgame portion of the engagement. The PlumeSat then collects this high-resolution plume imagery with both passive multi-spectral IR and active LADAR imagers as depicted in Figure 2.2. This imagery is then down-linked to the ground for plume-to-hardbody and aimpoint image analysis. An appropriate increase of  $\Delta v$  at the next apogee will return the PlumeSat to a safe near-circular parking orbit.

Using LLNL's patented pump propulsion technology we estimate that a PlumeSat can have between 1-2 km/s of  $\Delta v$ , sufficient to enable it to perform the 5 to 7 plume collection and fly-by experiments, that have been base-lined for this mission. This  $\Delta v$  range is a result of choosing either a non-toxic mono-propellant  $H_2O_2$  that would have 1 km/s of  $\Delta v$  or the base-line PlumeSat vehicle, that would incorporate a non-toxic bi-propellant (using  $H_2O_2$  and kerosene) with approximately 2 km/s of  $\Delta v$  capability for the mission. For either propellant load, it is estimated that

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<sup>1</sup> Clementine Moon Mapping mission was executed in 22 months (March 92 – January 94)

11<sup>th</sup> AIAA/MDA Technology Conference and Exhibit, Monterey, California, 29 July-2 August 2002.



from 5 to 7 boost phase data collects should be possible. For the lower case, higher fly-by altitudes at 200 km to 250 km would be used. The PlumeSat would have sufficient  $\Delta v$  margin to allow even a boost phase intercept experiment at the conclusion of the last phenomenology mission.

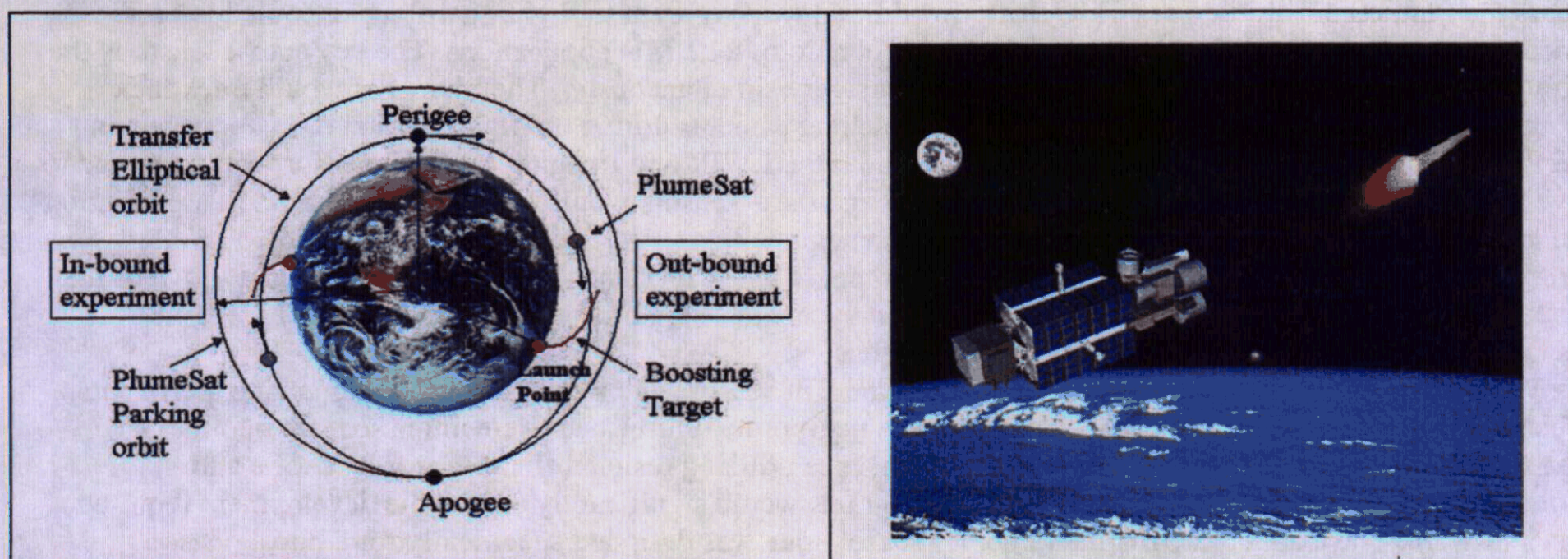


Figure 2.1 PlumeSat conceptual experiment approach; data collects can occur at either the in-bound or out-bound segment of the trajectory.

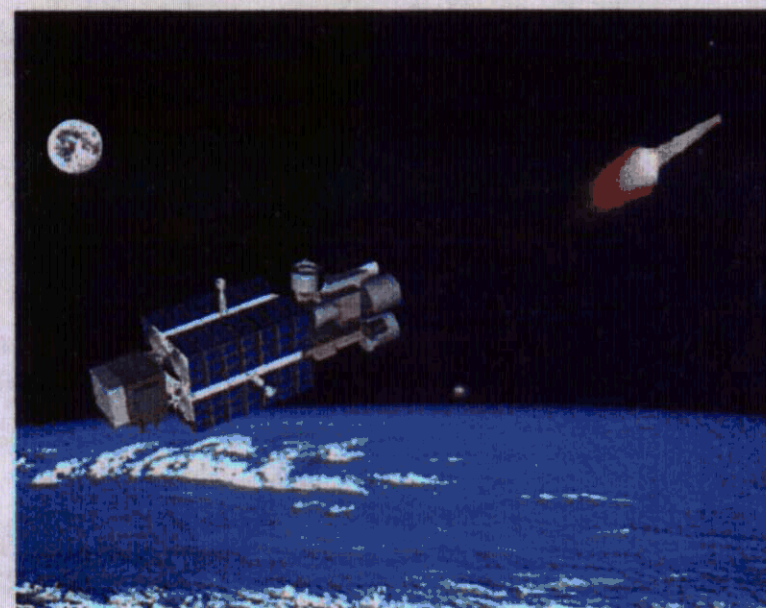


Figure 2.2 Shows a PlumeSat collecting imagery from a boosting target

### 3.0 PlumeSat Vehicle Configuration

The PlumeSat consists of a liquid divert and attitude control system (LDACS) that forms the structural backbone of the vehicle. Figure 3.1 shows the physical configuration of the PlumeSat along with a table denoting the mass allocations envisioned for this vehicle. The payload elements of this MicroSat are located at each end of the vehicle in a mass balanced configuration that allows for divert impulses from the DACS. The tanks in the DACS use pistons to manage the expulsion of the propellant(s) and enable the vehicle to maintain a fixed center-of-mass throughout its mission life. The PlumeSat has a solar array and battery pack mounted around the propulsion core as an external jacket. This enables the vehicle to recharge itself between data collects while it waits in a safe parking orbit.

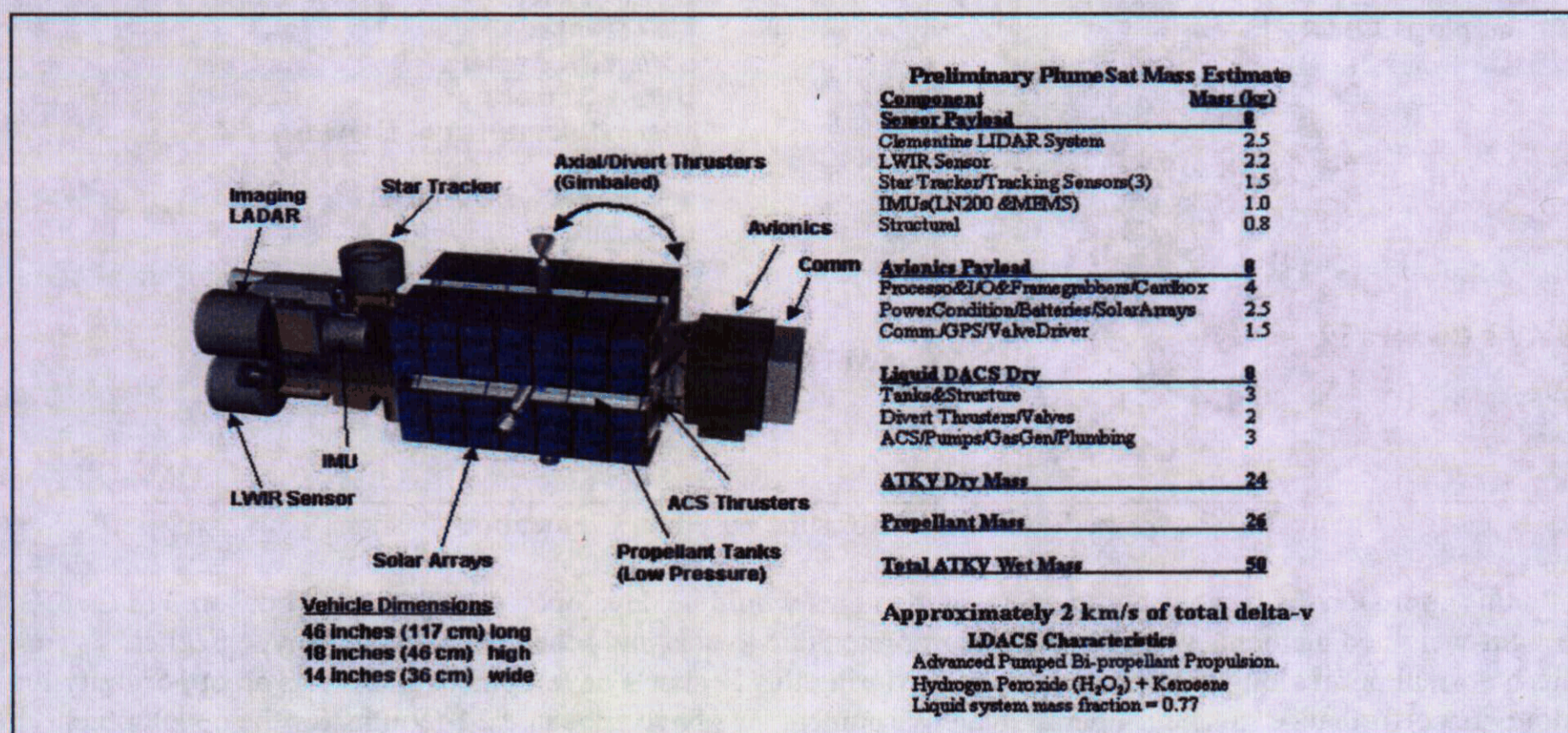


Figure 3.1 Preliminary PlumeSat hardware configuration and mass allocation



### 3.1 Sensor Payload Options

The sensor payload consists of a collection of residual refurbished Clementine sensors that have been either re-flight qualified or upgraded with new components. The sensor suite on the PlumeSat would include an imaging LADAR sensor, a LWIR sensor, a SW/MWIR camera, an UV/Vis camera as well as a Clementine Star Tracker used to update the PlumeSat's attitude and IMU drift. In addition we may want to flight qualify an uncooled micro-bolometer imager to evaluate the performance of this technology for BMD applications. The key active sensor is the Imaging LADAR sensor that provides both range and imagery simultaneously. The PlumeSat would track the boosting target with both its SW/MWIR and UV/Vis tracking cameras during the flyby portion of the engagement. As the PlumeSat begins closing on the boosting target both the LWIR and Imaging LADAR sensor would be used to observe the plume and hardbody with higher resolution and these sensors would both be used to support a prediction for the location of the hardbody and the aimpoint in the endgame imagery. The miniaturized uncooled LWIR imager would also observe the plume during flyby to compare its performance to the SW/MWIR imager. All of the collected imagery would be stored and then downloaded over time using one or more ground stations. Figure 3.2 shows the PlumeSat sensor suite based on Clementine sensors.

We are proposing two options to implementing the BPI sensor suite required for the PlumeSat experiments. The first and lower cost option would be to extensively incorporate refurbished Clementine sensors into the PlumeSat. This would be a relatively low risk approach since utilizing residual flight sensor hardware and components from the Clementine/Brilliant Pebbles programs would significantly reduce the development required for this hardware. The Clementine/Brilliant Pebbles sensor suite was designed specifically for a boost phase intercept mission and is therefore a near-perfect sensor suite for these phenomenology missions. Furthermore, the sensors themselves were already space qualified during the Clementine mission. Several sensor systems would be re-acceptance tested for flight and others would be refurbished mating their optical systems with more modern IR FPAs and their readout electronics.

An option to the Figure 3.2 design is to develop an engineering prototype of the Integrated Seeker for the Advanced Technology Kill Vehicle (ATKV). The ATKV is a concept vehicle design by LLNL that would support either boost phase or midcourse intercept missions. The Integrated Seeker that would be developed for the ATKV would incorporate both an active LADAR and passive multi-spectral LWIR imaging channels within a common optical system that can provide both boost phase and midcourse capability.

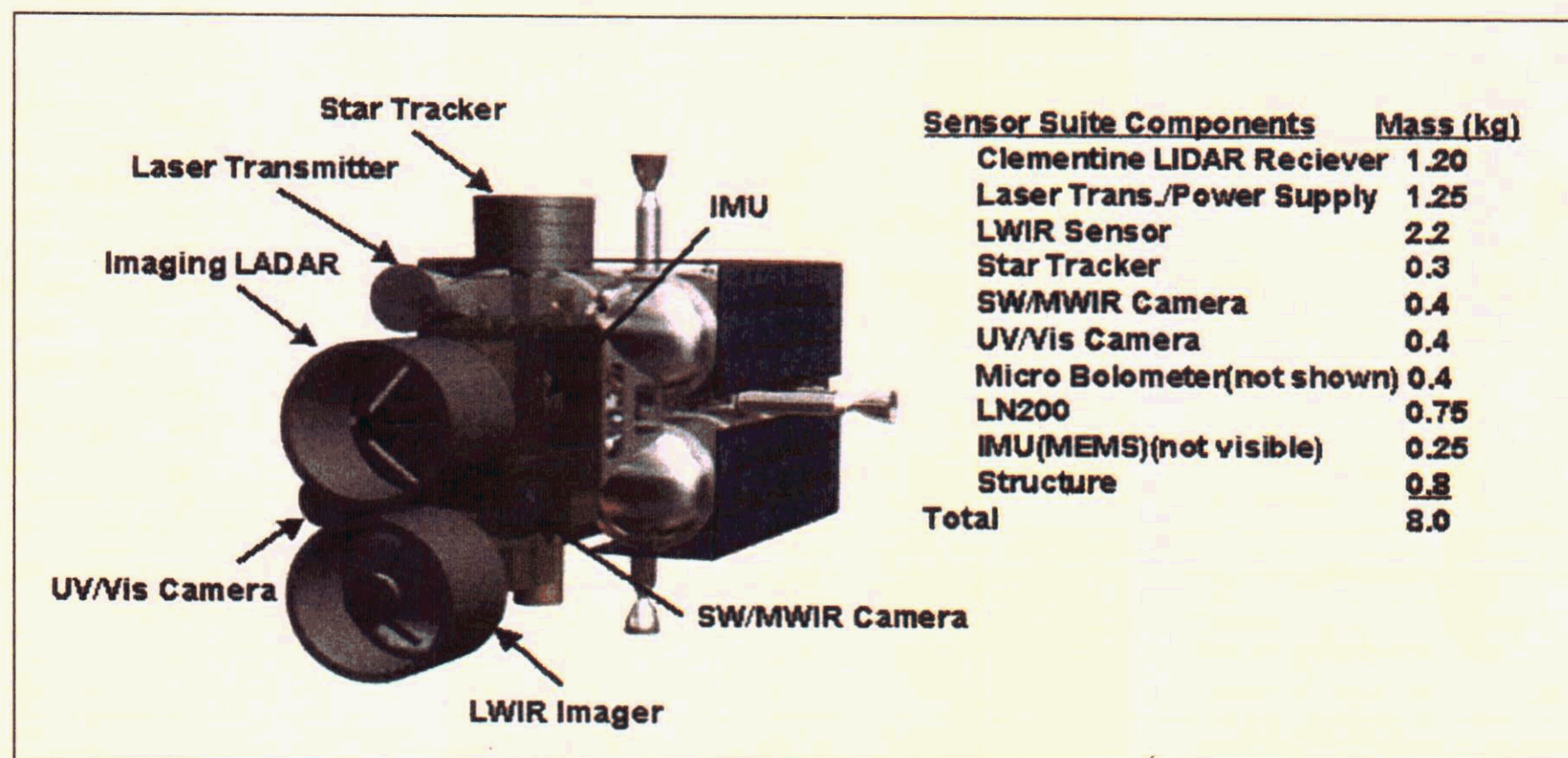


Figure 3.2 Shows the PlumeSat sensor suite based on Clementine sensors.

In this approach the basic prototype Seeker elements would be developed and integrated but some of the ultimate light-weighted elements would not be incorporated due to cost and schedule. This prototype Seeker represents a normal point along the development path during this Seeker's development and offers an opportunity to demonstrate its performance in a near-operational environment. We have allocated 24-months for the development of a PlumeSat. This is two months longer, than the time it took to develop the original Clementine spacecraft and sensors. So this should be sufficient time to develop a flight prototype of an Integrated ATKV Seeker for this



mission. The two-year delivery schedule for this vehicle, is possible because of the experienced MicroSat technology program team already in place at LLNL. This team has continued to push the integrated development of these lightweight high-performance MicroSat technologies and can rapidly move forward with this mission.

### 3.2 Propulsion Core

The liquid DACS propulsion system is based on the pumped propulsion system under development for the ATKV. Figure 3.3 shows the ATKV vehicle with its Integrated Seeker and propulsion system. This pumped propulsion system would be space qualified as part of a technology maturity demonstration that would be incorporated into the PlumeSat experiment. As discussed previously either a mono-propellant or bi-propellant configuration can be chosen for this vehicle. A bi-propellant system will have twice the  $\Delta v$  capability of the mono-propellant and is recommended for this mission.

### 3.3 Processor and Avionics

The PlumeSat avionics system is based on a high performance PowerPC processor and CompactPCI bus as shown in Figure 3.4. The PowerPC family is widely used in embedded systems for its performance and low power features. In addition, commercial versions of the PowerPC 603e have been tested, demonstrating significant inherent radiation tolerance. The CompactPCI bus is a high-performance, processor independent I/O bus, which provides an efficient path for processor upgrades such as to the PowerPC 750. The system supports modern, real-time embedded software development environments. This design allows rapid code development, debugging, and testing. Its modular design leverages COTS technologies, permitting early integration and test of both hardware and software elements. The chosen architecture provides a high performance solution for current and future MicroSat missions. This same architecture and design approach, is being adopted by major aerospace system providers. Projects are now underway at two contractors to develop radiation-hardened PowerPC CompactPCI modules.

The flight processor will be a COTS module with modifications for thermal management and radiation tolerant parts as needed. The MicroSat will use a commercially available solid-state error correcting storage unit for image data. The size of the disk(s) selected will be based on the specifics of the mission profile. During a mission sequence the PlumeSat will store on board the majority of imagery data collected for later down-link to earth. The specific telemetry capabilities are subject to both the on-board transceiver selected as well as the type of ground stations employed for the mission.

### 3.4 Communications

The communications module provides the interface between the on-board processor and the RF transceiver. For ground testing this hardware can be as simple as an Ethernet module that connects to wireless network components. Although the flight module must also have a port for ground testing, it connects to a transceiver that is compatible with satellite network hardware. A leading candidate RF transceiver is a novel low-mass SGLS-signaling AFSCN-compatible unit designed by the Naval Research Laboratory (NRL). More detailed information may be obtained by consulting the NRL Naval Center for Space Technology specifications SSD-S-CM013 and SSD-S-CM017. It has a nominal data rate of 1 Mbit/sec. A commercial transceiver unit, the MST-21 is also becoming available from SpaceDev that appears as a usable option for this application.

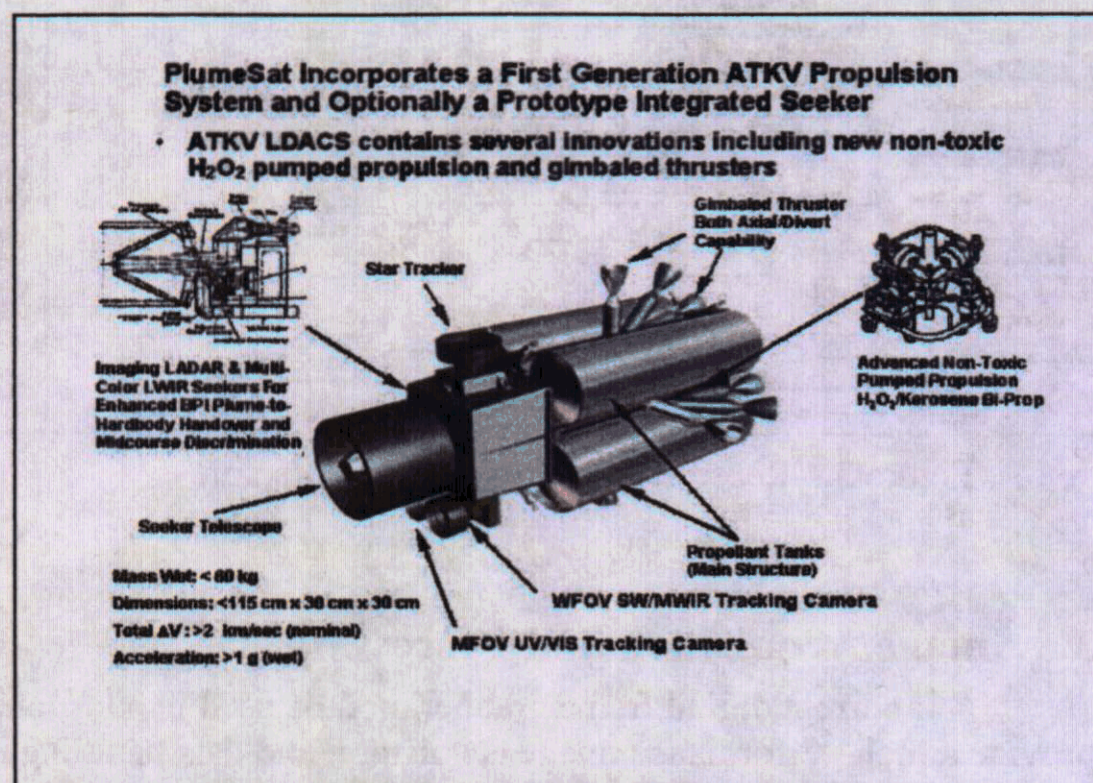


Figure 3.3 Shows the ATKV with its Integrated Seeker and liquid pumped propulsion system with its swivel divert and axial thrusters.



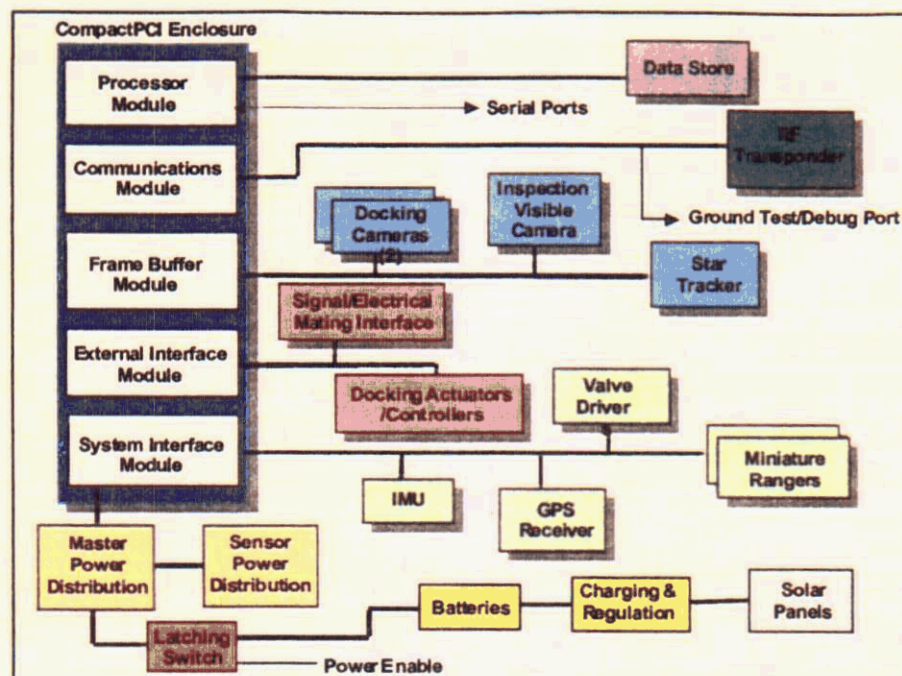


Figure 3.4 Representative avionics architecture

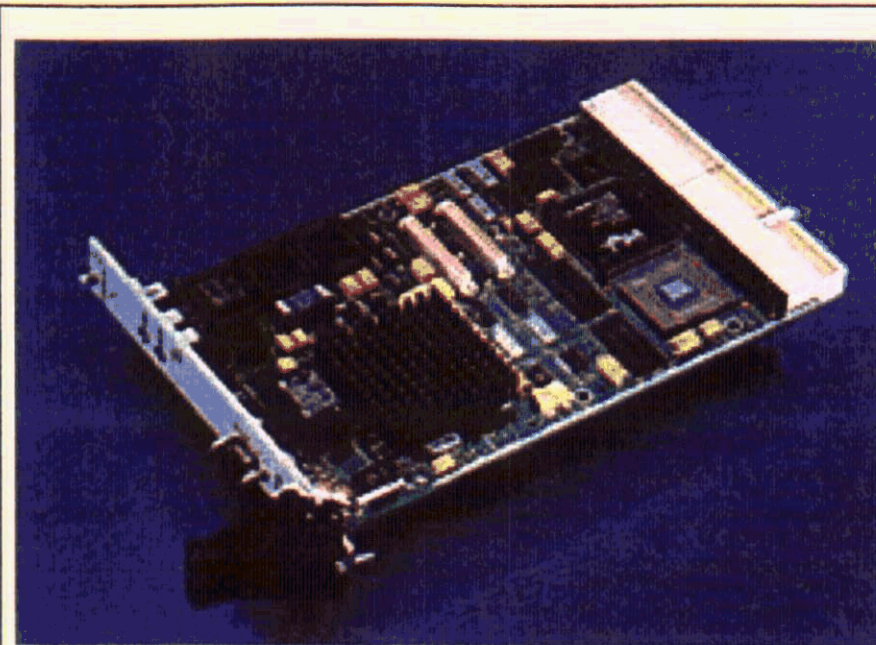


Figure 3.5 High-performance PowerPC 603e RISC CPU and utilizes a CompactPCI bus.

### 3.5 Image Acquisition and Processing

Our current digital frame grabber module used in our ground test vehicles, is a COTS board designed to provide a high-performance image acquisition and data handling interface between the CompactPCI bus and high-speed digital cameras. It features 8 to 16 bit pixels, pixel clock rates of up to 20Mhz, multiplexed operation for cameras sharing the video channel, Automated Imaging Association (AIA) digital camera compatibility, a Look Up Table (LUT) to allow real-time hardware functions such as thresh-holding, a 16K by 32 bit FIFO buffer to support DMA over the CompactPCI bus, and a Region of Interest (ROI) acquisition mode. For additional image processing capability, the frame buffer module could incorporate a commercial DSP board with local storage and an add-on mezzanine designed for hardware-based image compression. Any commercial hardware that has not already been flight qualified would need to be put through a qualification process and in many cases will require the redesign of the board to accommodate the flight environment.

### 3.6 Vehicle Control

The system interface module provides connection, control, and acquisition functions for the PlumeSat guidance and navigation elements. The current module is an Industry Pack (IP) carrier board that uses serial IP modules to communicate with the IMU, GPS, and sensor systems. A digital I/O module controls the valve drivers. Operations that require physical connections outside the PlumeSat would be handled via an external interface module. Though not considered as part of this vehicle baseline, these would include control of mechanisms used in docking and servicing missions such as robotic arms, grappling fixtures, and electrical connectors.

### 3.7 Power Distribution and Management Systems

For the PlumeSat we would plan to utilize Li-ion rechargeable batteries for the operation of this micro-satellite vehicle. There are a large number of options for these including some that are undergoing qualification for space under Air Force sponsored efforts. We have identified light-weight high energy capacity batteries developed by Polystor, Inc. as viable candidates for flight qualification. There are several advanced solar cell technologies that can be used for future flight vehicles. Dual-junction cells and concentrator arrays offer the ability to maximize power generation in very low mass and small areas. The body-fixed external jacket of solar arrays and rechargeable batteries would act as a thermal blanket over the DACS propulsion core.

A power management controller would monitor and control the power to all of the spacecraft loads. It communicates with the system processor to provide the capability to make mode changes, carry out power down commands to various components, and monitor the power system condition. This link also provides a way for the controller to signal the system processor of power system alarms and to alert it to the need for imminent shutdown. The PlumeSat would enter a power-down mode autonomously by the system processor as a result of preprogrammed mission operations or as a result of detecting battery depletion via the master power distribution module. A further means would be receipt and confirmation of a power-down command from the ground station.



### 3.8 Software

The MicroSat software development environment uses the VxWorks real-time operating system (RTOS). VxWorks is a commonly used, well-tested, RTOS that provides a rapid development environment for integration of new software modules. It is also portable among many processors. It has been used in space applications including the Clementine I spacecraft and JPL's Mars Pathfinder. Figures 3.6a and 3.6b show the hierarchical organization of our mission software and the GN&C mission software modules. Many software modules exist for GN&C, imaging, target tracking, and other real-time operating codes can be adapted for this satellite mission. As described in the introduction, our software environment supports the use of software uploads that enable the modification and tuning of our GN&C and image processing algorithms throughout the mission, enabling the earlier fly-by experiments to improve the performance of the subsequent fly-bys and will more likely enable a successful intercept at the conclusion of the phenomenology data collects.

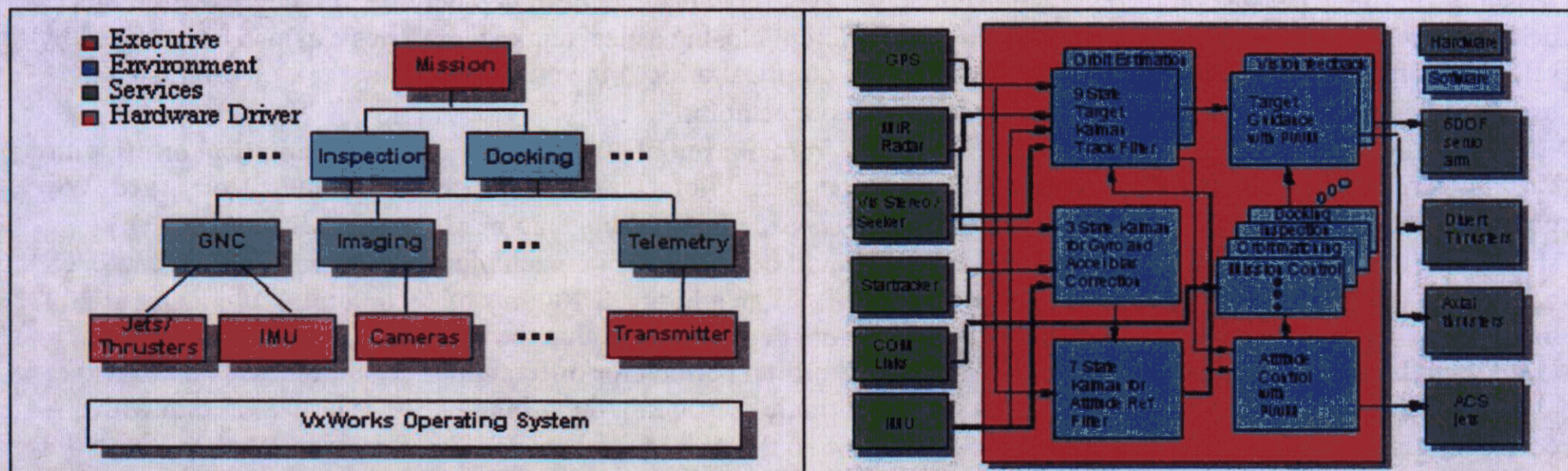


Figure 3.6a shows the software hierarchical structure of the real-time vehicle control software.

Figure 3.6b Guidance, Navigation, and Control mission software modules and interface drivers

### 3.9 Integrated Testing

Ground performance testing is the key to the success of a PlumeSat mission. It is crucial to be able to repeatedly practice and test the integrated vehicle's ability to perform precision orientation and translational maneuvers. These tests should include maneuvers to achieve orbit matching, rendezvous and the high-speed BPI flyby experiments. In addition we have already tested control algorithms that enable inspection and proximity-operations and docking. Ideally, one would like to have a 6 Degrees-of-Freedom (DOF) test environment. However, in most cases a 5 DOF or 4 DOF environment is sufficient.

In order to support the testing of integrated MicroSats, LLNL has developed 4 DOF and 5 DOF dynamic air bearing ground testing facilities. The 4 DOF facility includes an air rail with 3 degrees of rotational freedom and one degree of translational freedom. The 5DOF facility utilizes an air table with 3 degrees of rotational freedom and two degrees of translational freedom. These facilities enable low cost repeatable end-to-end performance testing of integrated MicroSat testbed vehicles, and full-up performance acceptance testing of final flight hardware and software before launch. Figures 3.7 and 3.8 show LLNL's air rail and air table test apparatus.

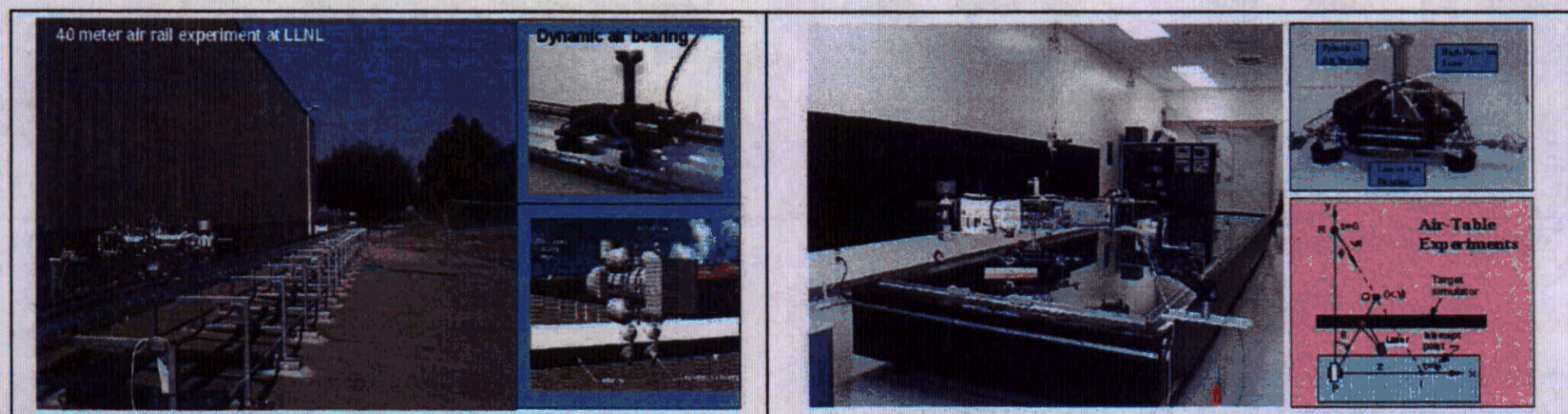


Figure 3.7 Dynamic Air Rail test apparatus

Figure 3.8 Dynamic Air Table test apparatus



#### 4.0 Mission Analysis

There are two key mission requirements for the PlumeSat operation: (1) total  $\Delta v$  and acceleration requirements of the spacecraft, and (2) closing kinematics during plume imagery collection. We will investigate these requirements in detail in this section. We recall Figure 2.1 that shows a typical scenario of a plume collection experiment. First a target launch location is determined. Given additional knowledge of the missile burnout velocity and position, the perigee of the new orbit can be decided say at point labeled "perigee". The apogee is then determined at point labeled "apogee" on the PlumeSat parking circular orbit. Once the perigee and apogee points are determined, the transformation into an elliptical orbit with same perigee and apogee points is possible. Knowledge of the orbital parameters allows us to determine the orbital period and thus the location of the PlumeSat as a function of time. To transform from a 400km circular orbit to an elliptical orbit with a perigee at a desired point requires a  $\Delta v$  change at the point chosen for the apogee [2]. The  $\Delta v$  maneuver is to reduce the orbital velocity so the PlumeSat falls quicker to the perigee point. The plume collection experiment can be designed within  $\pm 100$  degrees from the perigee point to simulate different crossing angles. Different closing aspect angle geometries can also be obtained by selecting different perigee altitudes. To return from the elliptical orbit to the original 400 km parking orbit, an exactly equal  $\Delta v$  is added to the orbital velocity at the apogee point.

Figure 4.1 shows the  $\Delta v$  needed for transferring from our initial 400 km circular orbit to elliptical orbits with varying perigee altitudes. Note that a nominal 0.3 m/s per each kilometer change in perigee altitude is observed. We noted that at a perigee of 100 km, almost 90 m/s of  $\Delta v$  is needed. By adding another 10 m/s to account for flyby slewing maneuvers, we concluded that a 100 m/s  $\Delta v$  would be sufficient for each plume collection experiment. We can restore the PlumeSat to its original safe parking orbit for an additional 100 m/s of  $\Delta v$  or a total  $\Delta v$  budget of 200 m/s. Figure 4.1 also plotted the orbital velocity at different perigees. Note that the lower the perigee altitude, the higher will be the orbital velocity. Figure 4.2 shows the orbital periods for different perigee altitudes. The lower the altitude, the shorter is the orbital period. At a perigee altitude of 100 km, the orbital period is only 89.5 min with a corresponding orbital velocity of  $\sim 7.93$  km/s. In addition to the  $\Delta v$  requirement for transferring to elliptical orbits for plume imagery collection, more  $\Delta v$  is needed for inclination and azimuthal changes. Figure 4.3 shows the angular rates during flyby and estimated  $\Delta v$  requirement for attitude control system (ACS) pointing and tracking. It is estimated that less than 5 m/s of  $\Delta v$  is needed per flyby.

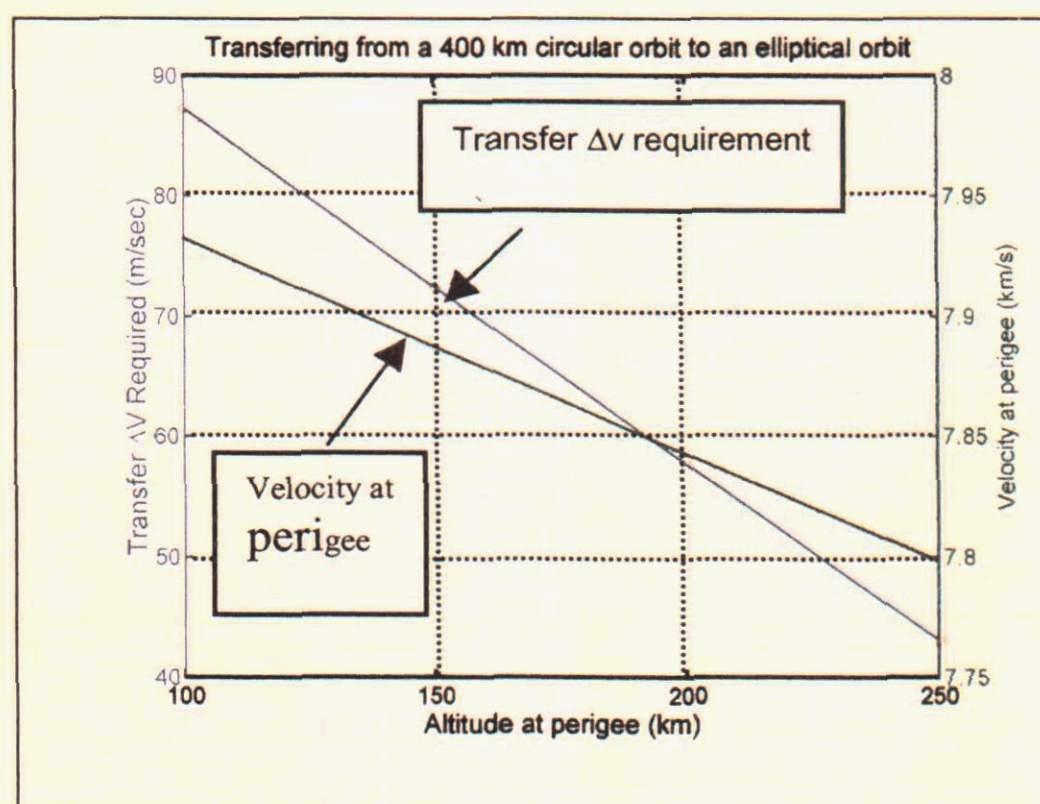


Figure 4.1  $\Delta v$  required to transfer to an elliptical Orbit for plume collection

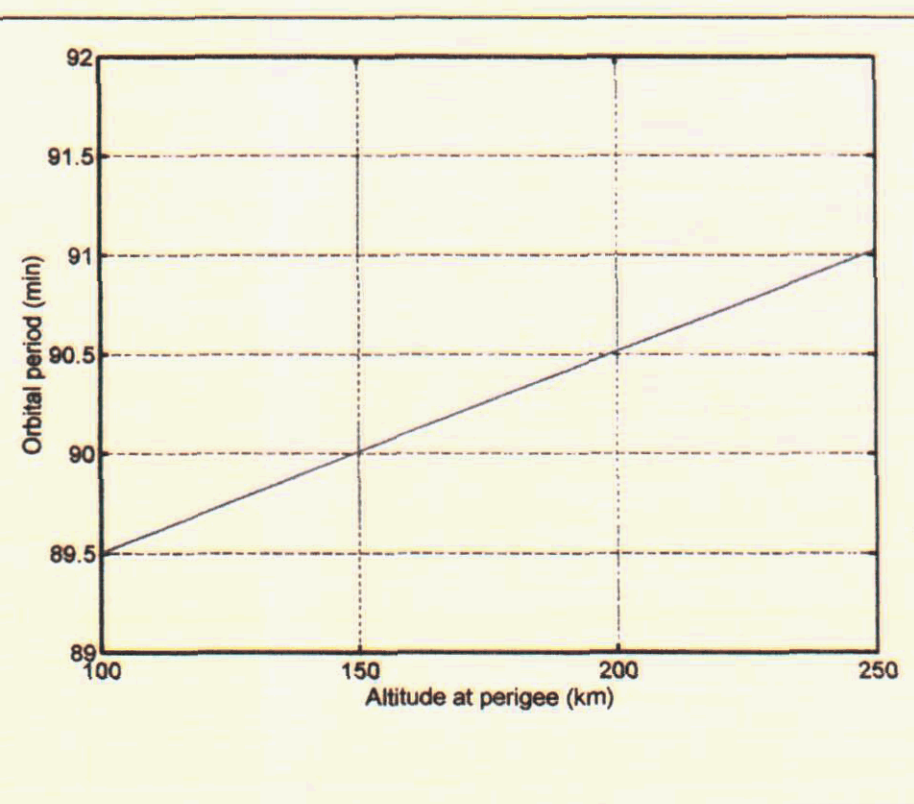
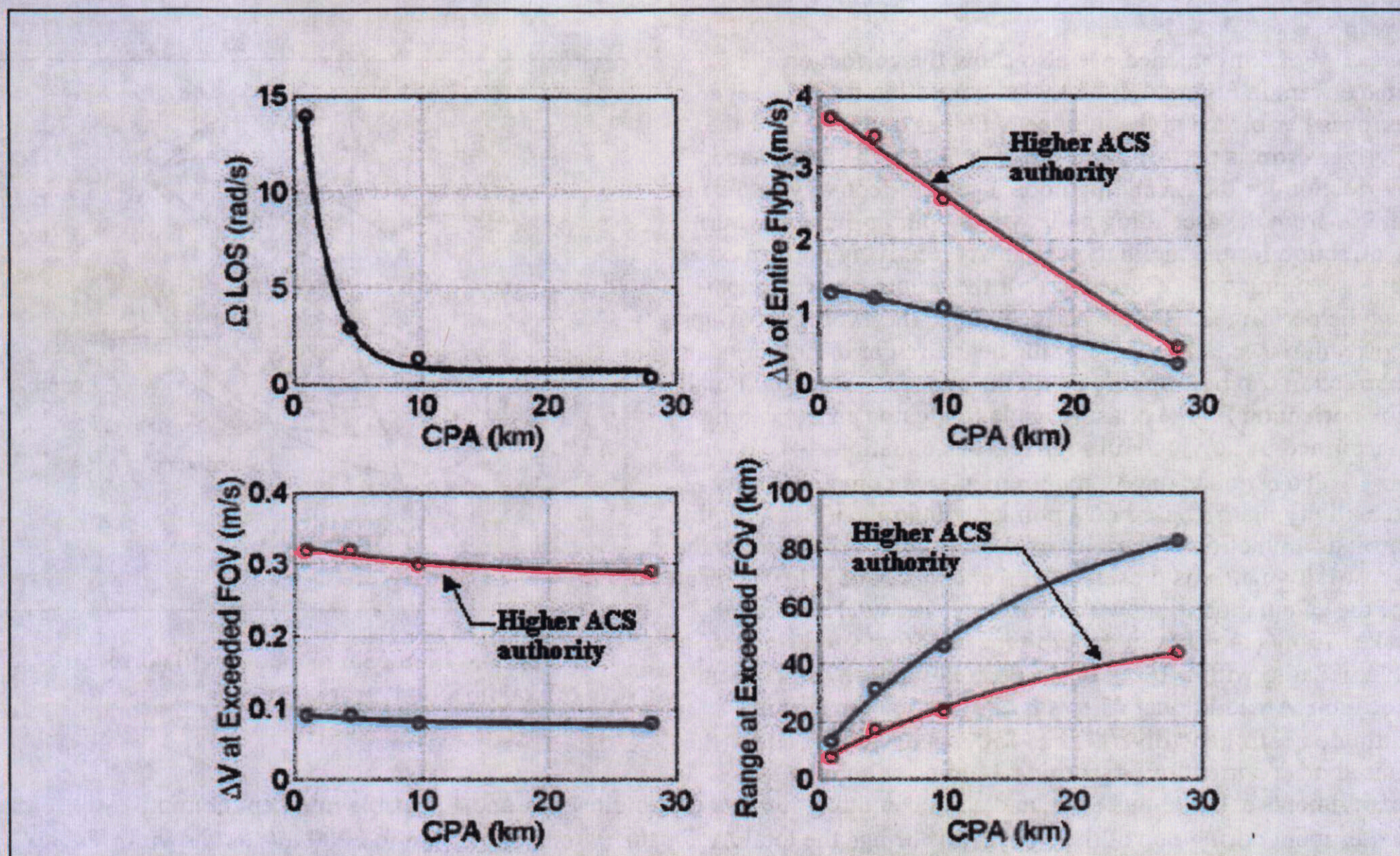


Figure 4.2 Orbital period of elliptical transfer orbit at different perigee



Figure 4.3  $\Delta v$  requirement for pointing and tracking of the target during flyby

#### 4.1 Delta-V Budget and Acceleration Requirement

We have previously established that approximately 200 m/s of  $\Delta v$  will be needed for each plume collection experiment. This requires a PlumeSat to leave its parking orbit, transfer to a data collection orbit and then transfer back to a safe parking orbit. Another set of  $\Delta v$  requirements are generated for establishing the desired initial orbital parameters immediately after launch. This discussion has been initially derived for cases where one desires to match the precise orbit of a specific resident space object (RSO), as in the case of an inspection or rescue mission. For the PlumeSat experiment, this discussion is provided for completeness and in case a particular ephemeris is required to insure specific viewing conditions over a given target launch complex. As an example, we assume that the PlumeSat will be launched by a Pegasus launch vehicle. Orbit correction  $\Delta v$  will depend on the orbital injection error caused by the Pegasus launch vehicle. From the Pegasus payload user guide[3], the orbit injection 3- $\sigma$  error is given in Table 4-1. Note that HAPS is the hydrazine auxiliary propulsion system that provides improved orbit injection state vector precision.

Table 4.1 Pegasus launch vehicle injection errors for a 741 km circular orbit.

Orbital Injection Error Type	Pegasus XL	HAPS Configuration
Apogee	$\pm 50$ km	$\pm 5.6$ km
Perigee	$\pm 50$ km	$\pm 5.6$ km
Inclination	$\pm 0.2^\circ$	$\pm 0.05^\circ$
Ascending Node*	$\pm 1^\circ$	$\pm 0.5^\circ$
Argument of Periapsis†	$\pm 1^\circ$	$\pm 0.5^\circ$

\* Estimate based on assumed 2 min launch window

† Estimate from 100  $\mu\text{rad}$  error in orbit injection flight path angle



For convenience, we also show the correction maneuvers in Figure 4.4. Note that correction for the apogee error is performed at the perigee, whereas correction for the perigee error is performed at the apogee. On the other hand, correction for the ascending node is most effectively performed at  $90^\circ$  from the ascending node with an out of plane  $\Delta v$  burn. Correction for the inclination is most effectively performed at the ascending node. Correction for the argument of periapsis can be performed near the perigee. Since the expected periapsis correction is small because of the near circular orbit, periapsis correction can be combined with the apogee correction. Finally the correction for the phasing angle (endgame chase) can be performed by solving Hill's rendezvous equations [4].

To estimate the  $\Delta v$  requirement, we compute the  $\Delta v$  sensitivity matrix based on a nominal 400km x 400km satellite orbit as a function of various error types. The derivation of the sensitivity matrix is presented in Appendix A of [5]. The result of the calculation is shown in Table 4-2 below. Note that it takes 75 m/s to perform the orbit match, 50 m/s to bring the PlumeSat to within 100m of the desired satellite deployment location. An additional 25 m/s is allocated for spacecraft attitude control and divert. Thus 150 m/s of  $\Delta v$  is used for the initial orbit correction. Assuming 7 plume collection experiments at a 200 m/s each, and adding another 450 m/s for contingency and a possible intercept homing experiment during one of the flybys, this brings the total  $\Delta v$  for the PlumeSat mission to 2000 m/s as shown in Table 4-2 below.

The PlumeSat acceleration requirement can be established using the criteria that an impulse burn of 100 m/s of  $\Delta v$  at apogee, to transfer to an elliptical orbit should induce less than 1% of out-of-plane  $\Delta v$  error. Given a spacecraft pointing error of less than one milli-radian, we obtain the constraint on the duration of the impulse burn of  $t < 1000/a$ . Choosing the acceleration  $a > 10 \text{ m/s}^2$  or greater than  $1g$  will result in a 100-seconds or less of burn time in which the spacecraft must maintain a pointing error of less than one milli-radian.

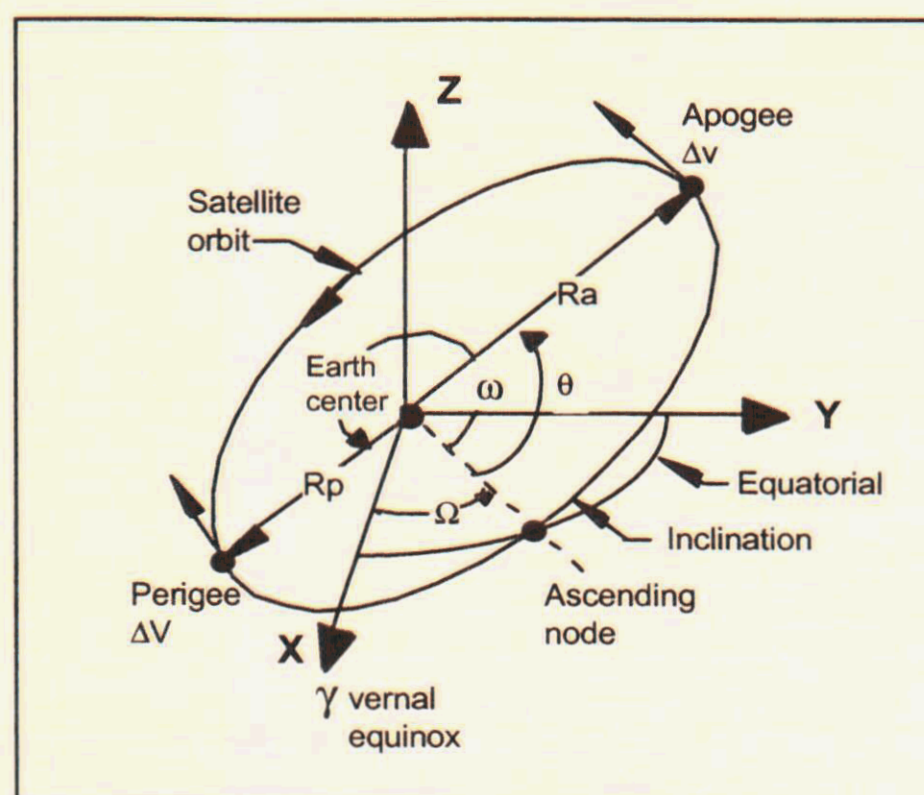


Figure 4.4 PlumeSat maneuvers to correct the orbital injection errors.

Table 4.2 Summary of total  $\Delta v$  requirements needed for a notional PlumeSat mission.

Correction Maneuvers	$\Delta v$ Sensitivity matrix	Assumed error ( $3\sigma$ )	Allotted $\Delta v$ (m/s) per maneuver
Perigee	0.28 m/s per km	5 km	2
Apogee	0.28 m/s per km	5 km	2
Ascending node	93.6 m/s per deg	0.5 deg	50
Orbit inclination	133 m/s per deg	0.05 deg	20
Argument of perigee	0.79 m/s per deg	0.5 deg	1
Correction to within 100m Of PlumeSat desired position		10 km	50
ACS			25
Mission requirement for 7 plume collection experiments @ 200m/s each			1400
Reserve for potential simulation of intercept homing maneuvers during flyby			450
<b>Total</b>			<b>2000</b>



## 4.2 Flyby Kinematics Analysis

Figures 4.5 shows the pertinent calculations of flyby parameters respectively for the in-bound trajectories. Out-bound trajectory parameters can be similarly obtained. Figure 4.4a depicts the line-of-sight (LOS) vector time history three minutes before the closest point of approach (CPA) against a target whose booster burns out at 197s. Small plume images showing the increases in plume size as the range reduces. Figure 4.4b depicts the PlumeSat flyby curves at different perigees. The angle of anomaly is measured from the perigee with respect to earth center. Finally figure 4.4c depicts the aspect angle (angle between the LOS vector and the target velocity vector) and the relative range. Note that the range changes 2000km in about 200s or a closing velocity of 10 km/s. The aspect angle ranges from 60 degrees to zero degrees at CPA. This range of aspect angles, are well matched to typical ground based, sea-based, air-based or space-based boost phase intercept scenarios. The PlumeSat can be timed so that a desired aspect angle can be achieved at target burnout.

If desired, the PlumeSat can also perform simulated intercept maneuvers during a flyby. These maneuvers can be executed using homing guidance software that nulls the zero-effort-miss distance to a specified miss distance from a desired target aimpoint. Measuring the accuracy of the miss from the offset aimpoint would yield important measurements of intercept performance without destroying the PlumeSat platform.

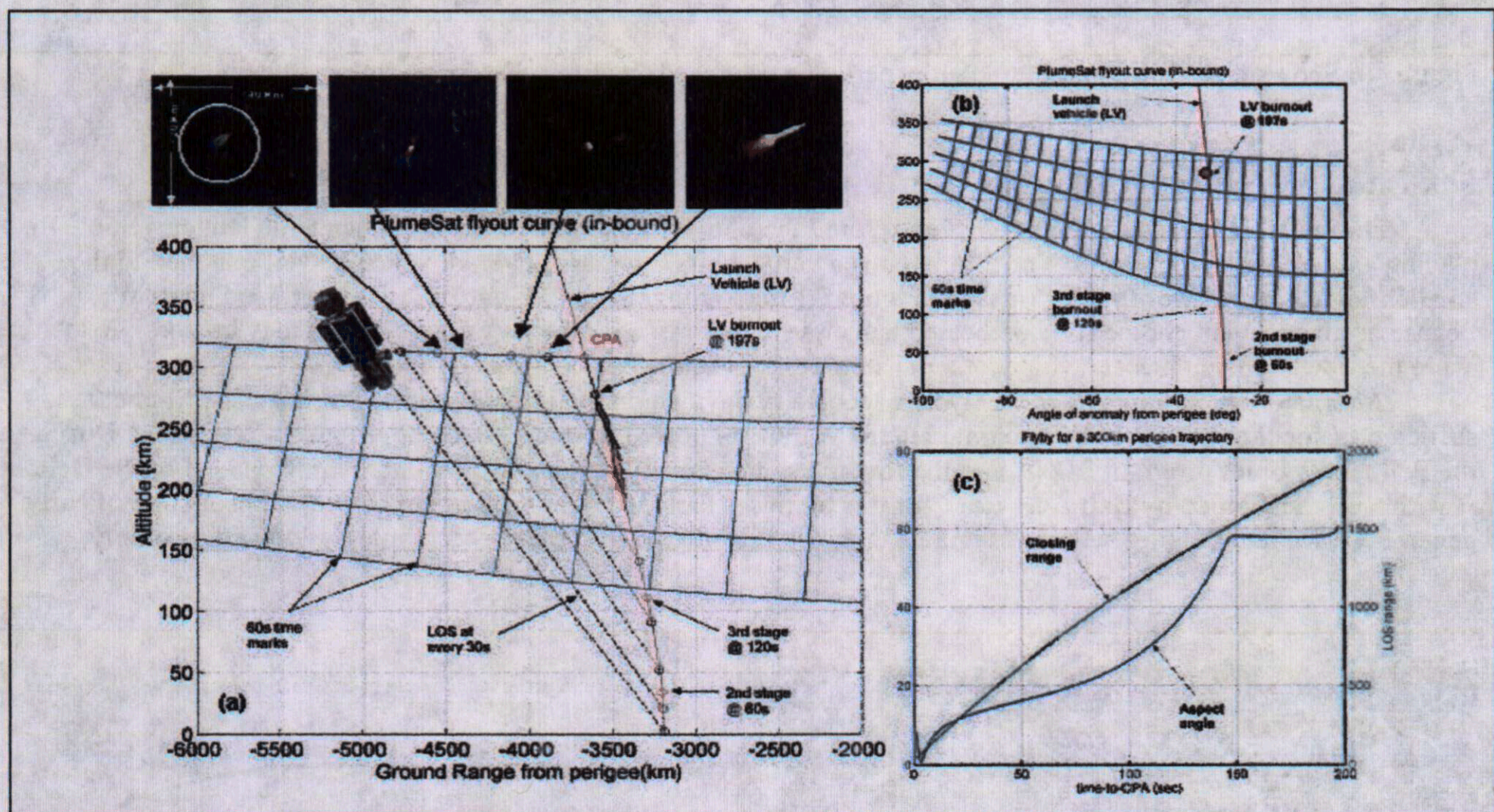


Figure 4.5 (a) In-bound PlumeSat flyout curves and LOS vectors showing collection of imagery in a closing geometry, (b) PlumeSat flyout curves, (c) Range and aspect angle as a function of time-to-CPA

## 4.3 Integrated Test of the Advanced Technology Kill Vehicle (ATKV)

An alternate or follow-on mission concept to the initial PlumeSat experiment is to use this same set of technologies to enable the in-orbit testing on an Advanced Technology Kill Vehicle designed for use in either boost phase intercept missions or midcourse engagements. This vehicle concept would incorporate many of the subsystems described above but with further integration and light-weighting to provide a very high mass-fraction vehicle with large  $\Delta v$  and high acceleration capability. The ATKV would incorporate a combined integrated passive and active seeker designed to support either boost phase or midcourse intercepts. This approach offers an opportunity to demonstrate the ATKV's Seeker performance in an operational environment. This second option opens the possibility to use the PlumeSat experiment as a flight test of the full up prototype ATKV. By designing all of the microSat life support elements as an external lifejacket that attaches to the basic ATKV interceptor, we can



operate the ATKV first as a microSat and then as a space based interceptor. Figure 4.6 illustrates this concept showing first the microSat mission phase and then the intercept demonstration where the on-orbit support lifejacket is shed to enable the ATKV to be tested with its full agility.

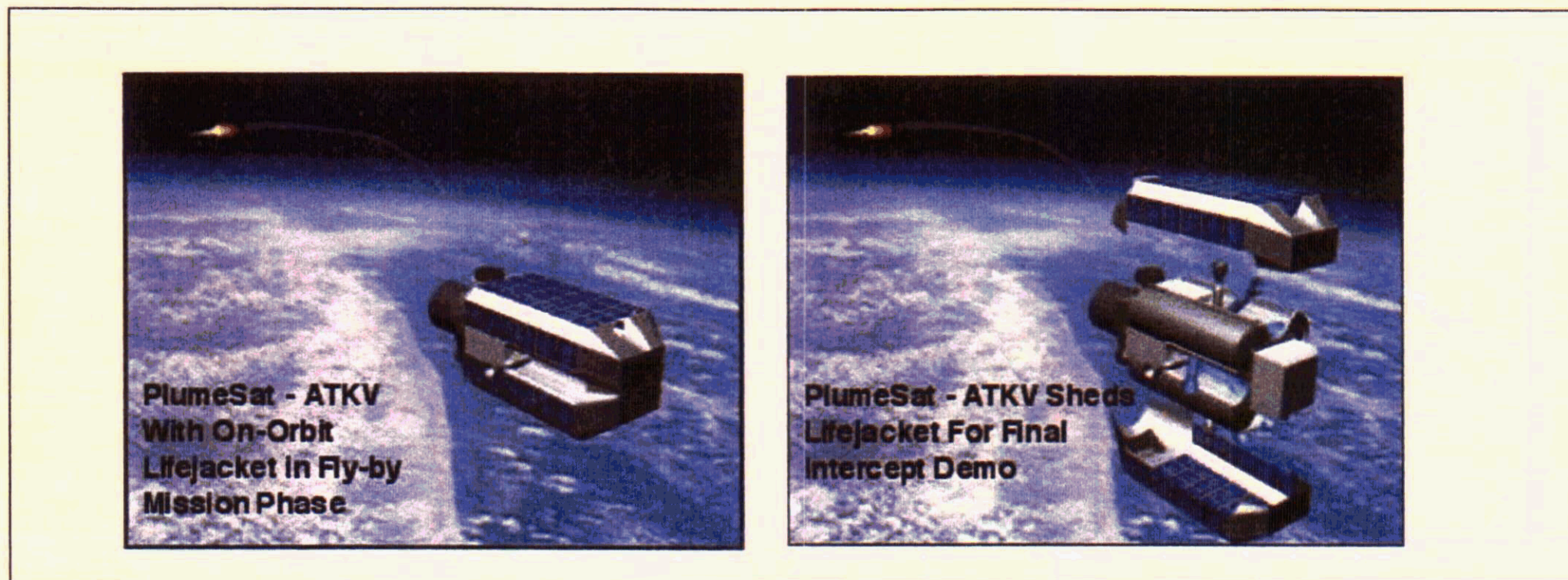
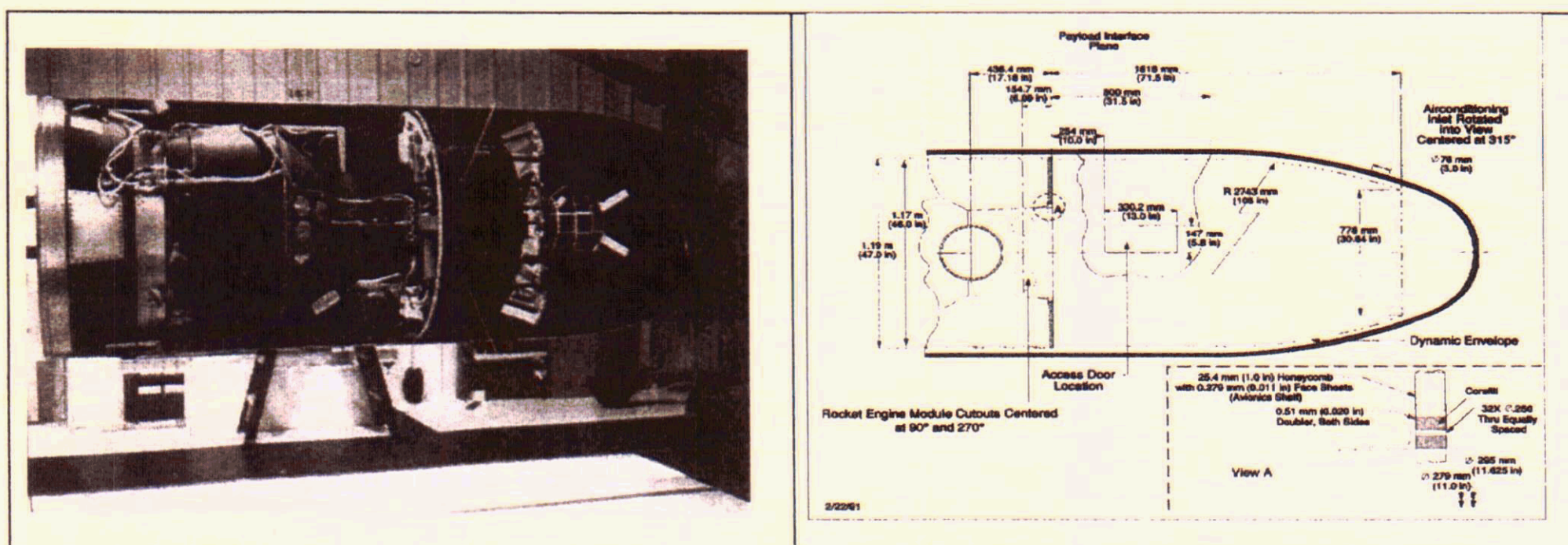


Figure 4.6 Shows the ATKV in a PlumeSat experiment as it sheds its lifejacket for an intercept demo.

## 5.0 Launch Vehicle Options

During a previous study[5], we have explored the option of using the Pegasus expendable launch vehicle for placing a micro-satellite in orbit. The PlumeSat is a very small, low mass payload, which is well matched to the smaller launch capacity of the Pegasus (see Figure 5.1 the Photograph and Figure 5.2 the Interface Diagram ). Pegasus is an excellent choice for a dedicated launch vehicle for the PlumeSat mission, and it may be possible to share the ride and launch costs with another customer if our orbits can be the same.

Alternately the PlumeSat could fly as a secondary payload on the Delta-II launch vehicle. The PlumeSat is sufficiently small that it could be integrated in the volume allocated for piggy-back or secondary payloads. During the Brilliant Pebbles program LLNL was the first to use this volume to launch a secondary payload off of the Delta-II with a bus developed by Ball Aerospace for this purpose. This early microsat incorporated a sensor suite of early generation Brilliant Pebbles sensors. Figure 5.3 shows this MicroSat during its final integration and assembly.





During the Clementine II Program the option of using a "free" ride on the Shuttle was also examined in some detail. The major attraction of a Shuttle launch is the reduced risk in using a manned launch vehicle, which will significantly reduce the launch risk to the payload. However, for this same reason the man rating tends to add costs and additional schedule impacts that can offset the lower launch risks. Another consideration is that the highest Shuttle orbital inclination is only around  $58^\circ$  which could limit the observational flexibility of the PlumeSat. In discussions with NASA, NRL, and AFRL during the Clementine II program, the consensus at that time was that while the Shuttle is the lowest risk launch option, there would be significant additional program costs and significant schedule impacts. Fundamentally LLNL is interested in seeing that the best choice is made for this program, and we are open to any reliable launch opportunity that could place the PlumeSat in a high inclination (near-polar) orbit.

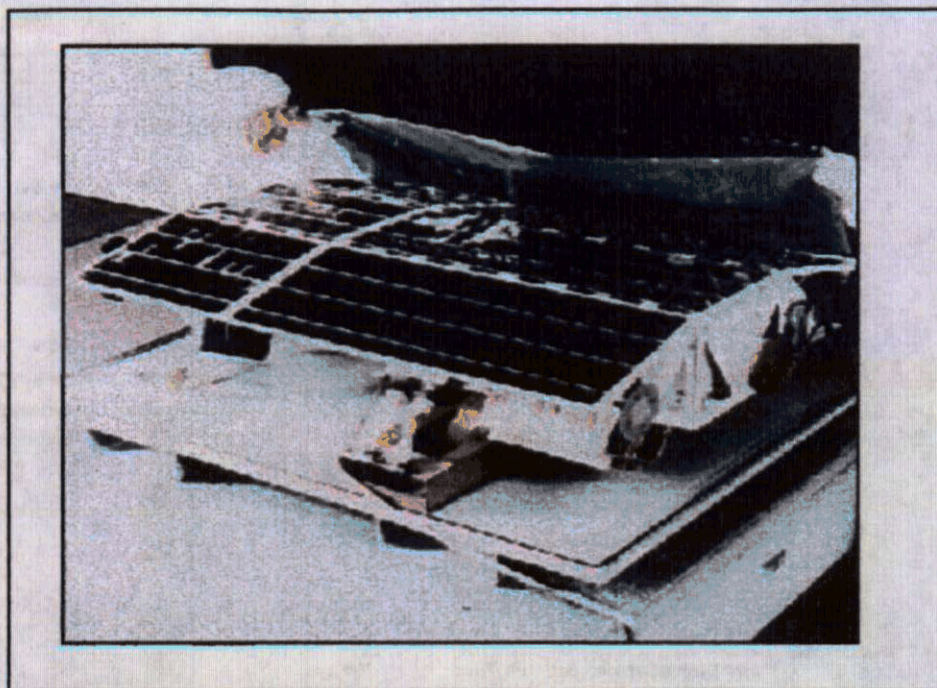


Figure 5.3 shows LLNL/Ball MicroSat vehicle during its final integration and assembly.

## 6.0 Summary

In this paper we analysed the feasibility of a PlumeSat data collection and intercept experiment using a lightweight agile Micro-satellite. The PlumeSat mission will provide MDA and the Department of Defense additional new capabilities: (1) multiple collections of high fidelity plume imagery from a realistic engagement scenario; (2) early flight demonstration of the Advanced Technology Kill Vehicle capabilities including the ability to practice the endgame homing strategy; and (3) a new access to space with an advanced capability Micro-satellite that can perform close-in inspection, formation flying, and other space logistic maneuvers.

LLNL believes a PlumeSat (<50kg) capable of autonomous orbit determination, navigation, and correction can be developed. It would perform precision flyby of boosting missile targets and collect plume imagery at multiple times. In addition this microSat platform could carryout a number of other experiments including the observation of RV and decoy offloads throughout the mission timeline. Future versions could also include the demonstration of docking with another space object and with further development even the capability to refuel these MicroSats could be realized. The PlumeSat would best be launched into LEO on an expendable launch vehicle in a high inclination orbit to offer access to a range of target launch sites. The PlumeSat would carry onboard a host of light-weight sensors, inertial navigation instruments and avionics and it would be equipped with a lightweight non-toxic pumped propulsion system that enables 1 km/s to 2 km/s of onboard  $\Delta v$  in a low mass package. LLNL's unique ground testing capabilities would enable extensive integrated ground flight testing and comprehensive mission flight software testing prior to launch. Figure 6.1 shows the preliminary proposed schedule and cost breakdown for the PlumeSat program. Cost ranges reflect the two sensor suite options (refurbished Clementine sensors or a prototype ATKV Integrated Seeker).



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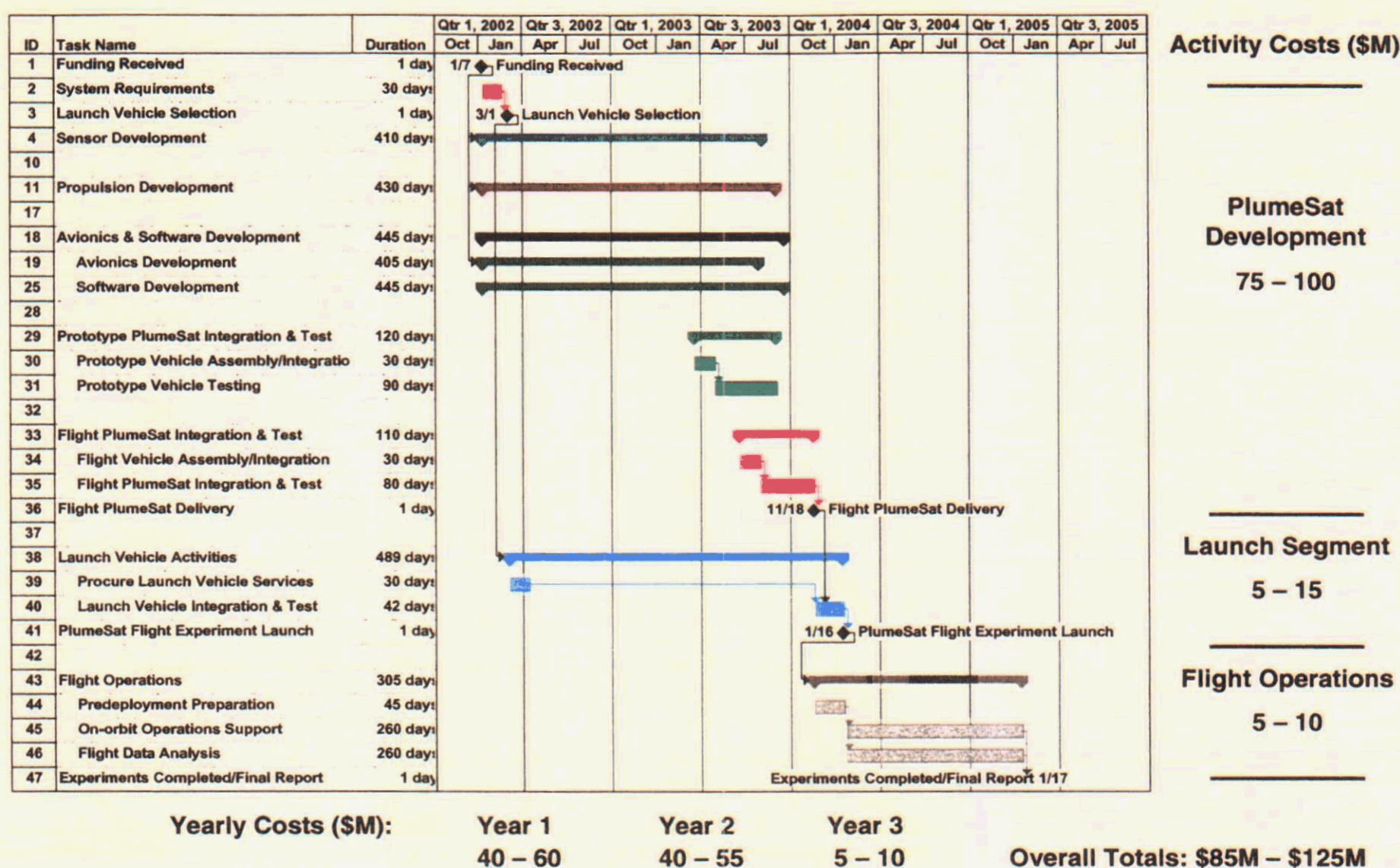


Figure 6.1 Preliminary Schedule and Cost Breakdown for the PlumeSat Program.

## 7.0 Summary Statement of Opportunity

With the ABM Treaty no longer a constraint and the renewed interest and commitment to enhance national security through better space management and organization, as well as the development of new technology to provide power projection in, from and through space as stated in Secretary Rumsfeld's recent commission report on space management [6], we believe that LLNL's proposed PlumeSat is just the kind of innovative technology that the commission's report is calling for. The PlumeSat vehicle system, when fully developed, would give the Department of Defense a new capability to access space. This system can both collect needed plume imagery in support of boost phase BMD, as well as open up a new set of capabilities in the use of space for surveillance, defense and logistical control.

## 8.0 References

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- [5] Ledebuhr, A.G. and Ng, L.C., and et. el., "MicroSat Rescue Demonstration Mission: A Feasibility Study," LLNL UCRL-ID-129880, Jan 30, 1998.
- [6] Rumsfeld report of the "Commission to Assess United States National Security Space Management and Organization," January 11, 2001.